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Diameter Caps and Forest Restoration

Evaluation of a 16-inch Cut Limit on Achieving Desired Conditions

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Summary

With forest plan revision in the U.S. Forest Service, the Southwestern Region is evaluating means for achieving desired conditions of the region. Some forests within the region have previously applied a diameter cap cutting limit as a means of responding to public concerns over the preservation of large diameter trees in forested ecosystems. We analyzed the effects of a 16-inch cap on forest structure in the coming decades, and the ability of managers to achieve and maintain desired conditions within two major forest ecosystems—ponderosa pine and dry mixed conifer. The effects of a cap on forest composition and fire behavior were also considered. The results suggest that a blanket policy of diameter-limit cutting impairs the ability of resource managers to achieve or maintain desired conditions, and is not sustainable in the mid to long term.

Keywords

Uneven-aged management, forest restoration, diameter cap, diameter cutting limit, desired conditions, ponderosa pine, dry mixed conifer.

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Cover: Photo taken by David A. Conklin, of the U.S. Forest Service Southwestern Region forestry staff, showing a ponderosa pine stand on the Mescalero Indian Reservation in southeastern New Mexico. The photo represents a managed uneven-aged forest stand structure and desired conditions for ponderosa pine forests of the Southwestern Region.

Introduction

Each national forest and grassland of the U.S. Forest Service (USFS) develops and periodically revises a land and resource management plan known as a "forest plan" as its chief policy document. The forest plan addresses the management of its resources with a framework of goals, standards, and guidelines. As outlined in the provisions of the 1982 Planning Rule (USDA Forest Service 1999; 36 CFR § 219), desired conditions are descriptions of goals to be achieved at some time in the future. Desired conditions, by their contributions to social, economic, and ecological sustainability, are the vision that drives the forest plan revision and implementation process. While the planning rule is currently under revision, the concept of desired condition is likely to persist. The proposed rule issued in February 2011 states that "A desired condition is a description of specific social, economic, and/or ecological characteristics of the plan area, or a portion of the plan area, toward which management of the land and resources should be directed" (draft new rule section 219.7(d)(10(i))). The 1982 rule (USDA Forest Service 1999) states that "The forest plan shall contain the following…multiple-use goals and objectives that include a description of the desired future condition of the forest or grassland…" (Section 219.11) with the following purpose and principles from Section 219.1:

> (a)(1) "The resulting plans shall provide for multiple use and sustained yield of goods and services from the National Forest System in a way that maximizes long-term net public benefits in an environmentally sound manner;
>
> (b)(1) "Establishment of goals and objectives for multiple-use and sustained-yield management of renewable resources without impairment of the productivity of the land;
>
> (b)(2) "Consideration of the relative values of all renewable resources, including the relationship of nonrenewable resources, such as minerals, to renewable resources;
>
> (b)(3) "Recognition that the national forests are ecosystems and their management for goods and services requires an awareness and consideration of the interrelationships among plants, animals, soil, water, air, and other environmental factors within such ecosystems; and
>
> (b)(4) "Protection and, where appropriate, improvement of the quality of renewable resources.…"

Desired conditions are an expression of ecological, economic, and social sustainability toward which management of the land and resources is to be directed over the life of the forest plan. Ecologically speaking, they describe species composition, structure, and landscape pattern. Desired conditions also incorporate the natural processes such as nutrient cycling, trophic interactions, fire, insects, and diseases. For forests and woodlands, desired conditions include age class diversity, tree density, overstory and understory composition, and the size and density of snags and woody debris. Desired conditions are aspirations and are not commitments or final decisions approving projects and activities. Ecosystem-based management may require long planning horizons and must, therefore, incorporate dynamics—spatial and temporal changes resulting from vegetation growth and succession and the periodic resetting of these by natural and human-caused disturbances such as fire, wind, insects, and tree harvest. For some plant communities, desired conditions may be achieved in a single management entry, followed by continued natural or human maintenance. For others, desired conditions may not even be achieved except over a long time period, involving multiple successive entries.

The Southwestern Region has established desired conditions for the management of vegetation across all major ecosystems of the region (USDA Forest Service 2010). Ecosystems are analyzed using a framework of potential natural vegetation types (PNVTs) (TNC 2006), a coarse map unit scheme building on similarities in site potential and historic fire regime. Desired conditions are described in terms of the variability of vegetation patterns across spatial and temporal scales within the respective PNVTs. Vegetation is quantified and categorized in terms of vegetation structure, composition, and dynamics to help characterize the desired vegetation conditions.

The Southwestern Region's desired conditions were developed by an interdisciplinary team that utilized historic range of variation concepts as a beginning point. Historic conditions (prior to approximately 1880) provide a strong inference of ecological sustainability (reference condition). Descriptions of historic conditions were modified for the desired conditions based upon socioeconomics, operational feasibility, Agency policy and direction, and legal requirements such as the Endangered Species Act. Other social, political, and economic factors are much different today than a century ago and there are valid considerations for leaving uncharacteristically high densities in some areas to meet management needs (USDA Forest Service 1992). Desired conditions are broad in theme and may require further modification based on the best available science or on specific management concerns and issues.

Desired conditions, particularly for dry forest systems, reflect a careful balance among ecological, economic, and social sustainability considerations. Identifying this balance is especially challenging in ponderosa pine and dry mixed conifer forests (AKA mixed conifer—frequent fire), where much of the region's social and economic desires for preservation and commodity production come to bear, and where much of the region's management activities are concentrated. The resulting desired conditions form standard regional direction for these systems, each reflecting overall sustainability, including the economic realities of the limited management options to restore and maintain desired composition and structure. In this study we focus on the ponderosa pine and dry mixed conifer PNVTs where diameter caps are the most relevant in regards to desired conditions and forest restoration.

Ecosystem Description

Ponderosa Pine Forest

The ponderosa pine forest ecosystem is widespread in the Southwest, occurring at elevations typically ranging from 6,000 to 7,500 feet (1,800 to 2,300 m) on igneous, metamorphic, and sedimentary parent soils with good aeration and drainage, and across elevational and moisture gradients (Fitzhugh et al. 1987, Romme et al. 2009). As currently described, this PNVT is comprised of both the "ponderosa pine/bunchgrass" (PPG) and "ponderosa pine/Gambel oak" (PPO) subclasses (Muldavin et al. 1996), collectively referred to as ponderosa pine forest. The dominant species in this system is ponderosa pine (*Pinus ponderosa* C. Lawson var. *scopulorum* Engelm.). Other trees, such as Gambel oak (*Quercus gambelii* Nutt.), pinyon pine (*Pinus edulis* Engelm.), evergreen oak trees (*Quercus* L.), and juniper species (*Juniperus* L.) may be present. There may be a shrubby understory mixed with grasses and forbs, although this type sometimes occurs as savannah with extensive grasslands interspersed between widely spaced clumps or individual trees. This system is adapted to drought during the growing season, and has evolved several mechanisms to tolerate frequent surface fires (Ffolliott et al. 2008). Historically, plant communities had over 10 percent tree canopy cover by definition of the PNVT. On contemporary landscapes, much of this type is dominated by closed forest structure (>30 percent tree cover) as a result of fire suppression and other past management practices.

Dry Mixed Conifer

The dry mixed conifer PNVT (AKA mixed conifer—frequent fire) spans a variety of semimesic environments in the Rocky Mountain, Colorado Plateau, and Madrean biomes of the Southwest. Mixed conifer forests are typically found at elevations between 5,000 and 10,000 feet (1,500 to 3,050 m), often situated between ponderosa pine forests below and wet mixed conifer (AKA "mixed conifer with aspen") or spruce-fir forests above (Romme et al. 2009, Sesnie et al. 2009). For the most part, this frequent fire type occupies warmer and drier sites of the mixed conifer life zone, and are characterized by an historic fire regime of frequent (9 to 22 years; Baisan and Swetnam 1990; Dietrich 1983; Grissino-Mayer et al. 1995; Heinlein et al. 2005), low severity surface fires and infrequently mixed severity fires. Typically these types were dominated by ponderosa pine in an open forest structure (<30 percent tree cover) with Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *glauca* (Beissn.) Franco) and minor occurrence of quaking aspen (*Populus tremuloides* Michx.) and white pines (*Pinus strobiformis* Engelm. and *P. flexilis* James). Aspen in the dry mixed conifer (DMC) occurs within inclusions of dissimilar site potential and not as a seral cover type as it does within the wet mixed conifer type (Moir and Ludwig 1979). More shade tolerant conifers, such as Douglas-fir, white fir, and blue spruce (*Picea pungens* Engelm.), tend to increase in cover in late succession, and would not typically achieve dominance under the characteristic fire regime (Brown et al. 2001, Heinlein et al. 2005). These species could achieve dominance in localized settings where aspect, soils, and other factors limited the spread of surface fire. Historically plant communities had over 10 percent tree canopy cover by definition of the PNVT. On contemporary landscapes, much of this type is dominated by closed structure (>30 percent tree cover) and climax conifer species as a result of fire suppression and other past management practices.

Historically ponderosa pine and dry mixed confer PNVTs were composed of mosaics of tree groups of one to many trees dominated by ponderosa pine in a generally uneven-aged structure, with occasional groups of even-aged forest structure present (Fule et al. 1997, Moore et al. 1999, TNC 2006). An understory of grasses, forbs, and sometimes shrubs was present and carried frequent surface fire. In the DMC PNVT, Douglas-fir frequently codominated plant communities with ponderosa pine. The abundance of Douglas-fir and other more shade tolerant tree species was limited by the high frequency of fire disturbance that favored the dominance of ponderosa pine due to its fire resistant characteristics. Historical inventories of ponderosa pine forests in the Southwest provide insight into structure conditions that are characteristic of these systems. From Woolsey (1911):

> "The typical western yellow pine forest of the Southwest is a pure park-like stand made up of scattered groups of from 2 to 20 trees, usually connected by scattering individuals. Openings are frequent, and vary greatly in size. Within the type are open parks of large extent…. In pure stand of yellow pine the ground cover is usually pine grass, bunch grass, and in openings grama of various species. The grasses are distributed in clumps or patches, interspersed with layers of pine leaves of various depths, according to the density of the sand [sic]. Underbrush is rare… Varying age classes give pure western yellow pine a variety of aspects. In places it is made up of thrifty pole stands of blackjack, with an occasional mature yellow pine fast declining in vigor. In others there may be an old mature stand of veterans, with complete reproduction beneath."

Three separate areas on the Kaibab National Forest in northern Arizona, ranging from 128 to 6,000 acres (52 to 2,430 ha), that were inventoried by Woolsey (1911) averaged about 30 ft^2/ac (7 m^2/ha) tree basal area. One sample area of about 500 acres (200 ha) on the northern rim of the Grand Canyon, had a basal area of about 55 ft^2/ac (13 m^2/ha)(Lang and Stewart 1910). This description is dated from about 25 years after the onset of heavy livestock grazing and the disruption of the characteristic fire regime to suggest that forest conditions may have been even more open than what are described in this excerpt.

Desired Conditions – Ponderosa Pine Forest and Dry Mixed Conifer

The following description of desired conditions was abstracted from guidelines written for the USFS Southwestern Region (USDA Forest Service 2010). The description describes forest structure, composition, process, and spatial pattern for the ponderosa pine and dry mixed conifer systems.

Uneven-aged forest structures comprise a distribution of age classes within stands. Overall, the landscape is generally dominated by ponderosa pine, the tree species most resilient to wildfire effects. Juniper, pinyon, oak, and other hardwood species are collectively well represented depending on the plant association, and are regenerating successfully where local forest biophysical conditions are appropriate for development of these species. Aspen can occur in inclusions of dissimilar site potential. Overall, forests are vigorous with characteristic levels of native insect and disease occurrences. In the DMC Douglas-fir and white pine can occur as codominants. White pine is present through much of this PNVT, with a wide range of genetic diversity, and regenerating in suitable locations.

In both the ponderosa pine and dry mixed conifer systems, a variety of forest density, spatial arrangement, and age and structure conditions exists across the landscape similar to historic conditions. Conifer forest types are composed of a distribution of age classes that comprise a sustainable mix of structural stages (early, middle, and late succession). Forest canopy gaps and openings occur on 20 to 40 percent of each stand area, with the exception of designated Mexican spotted owl habitats, and goshawk nesting areas where canopy cover is more continuous, but gaps can still be present. These canopy gaps and forest openings mimic historic spatial patterns and provide for the regeneration of ponderosa pine and the development of herb and shrub species, and facilitate reintroduction and maintenance of frequent surface fire as an ecological process. Forest canopy gaps and openings are dynamic over time, shaped by small-scale disturbances including fire and subsequent vegetation development, with some areas regenerating new tree groups of one to many trees, while other areas remain as openings that contribute to ecosystem diversity by supporting tree group rooting zones and grass-forb and shrub habitat. Managed uneven-aged stands range from 15 to 45 percent of maximum stand density index (see appendix B). In areas outside of MSO nest/roost and replacement nest/roost habitats, basal areas average less than 80 ft^2/acre (18 m^2/ha), and bark beetle hazard is low. In most cases, ponderosa pine and mixed conifer forest stands exhibit open and uneven-aged characteristics (multistoried), except for stands managed for goshawk nest and MSO nest/roost and replacement nest/roost habitats (MSO habitat may or may not be multistoried).

Dwarf mistletoe is an element of the forest landscape. There is a varied level of mistletoe across the landscape, comparable with historic conditions (Conklin and Fairweather 2010) such that it does not impede achieving and sustaining desired uneven-aged forest conditions. Desired stand dwarf mistletoe infection levels do not exceed 20 percent infection of the host species (trees per acre basis) or 25 percent of the area infected for any given tree species. Dwarf mistletoe infections are irregularly distributed among tree groups, such that effects are limited to the forest group scale.

Detailed descriptions of desired conditions are in appendix A.

Diameter Cap

An issue confronting the implementation of forest desired conditions is the concept of a diameter cut limit imposed with harvest prescriptions. In the past, diameter caps have been used as a means to preserve large trees, often those over 16 inches (23 cm) in diameter, leading to a so-called "16-inch cap." The approach originated in the environmental community over concerns for the preservation of large trees including:

- Impression that there are relatively few large trees remaining on the landscape (Abella et al. 2006);
- Loss of large trees through commercial logging;
- Harvesting trees is aesthetically unappealing; and
- The removal of large trees is a return to commercially-focused logging (Coughlan 2003, Larson and Mirth 2001).

The 16-inch threshold is an arbitrary value given its relation to forest restoration and desired conditions. There may be instances where the removal of small diameter trees (that happen to all be less than 16 inches in size) favor the desired tree age distribution and the restoration of an uneven-aged system. We differentiate the intent of such a prescription from an indiscriminate, broadly applied diameter cap, when considering disparities between existing and desired conditions.

Previous compromises were negotiated among local stakeholders resulting in project-level agreements to implement diameter caps. Diameter caps have since become a common practice on some national forests (Abella et al. 2006, Coughlan 2003, Fule et al. 2006, Larson and Mirth 2001). The few related empirics that have been generated to date suggest that such a policy is unsustainable (see "Related Studies"). The Southwestern Region has concerns that such constraints will limit achievement and maintenance of desired conditions for long-term forest structure, composition, and dynamics, particularly in frequent fire types characterized by open tree canopies and multistoried conditions.

Related Studies

Abella and others (2006) recently assessed the effects of diameter cap constraints in ponderosa pine forest restoration focused treatments and considered arguments for and against the approach. Treatment objective outcomes were similar to Forest Service desired conditions: the treatment guidelines focused on reduction of tree densities to within historic ranges, and reestablishment of presettlement tree patterns of one to several trees clumped among forest openings, based on historical evidence (Covington et al. 1997). In the diameter cap scenario, guidelines were implemented only as the 16-inch cap would allow. Results are summarized here:

- Final basal area was 87 and 39 ft^2/acre (20 and 9 m^2/ha) for the cap and no-cap treatments, respectively, a difference of approximately 50 ft^2/acre (11 m^2/ha).
- Where there were relatively few trees greater than 16 inches in diameter in the current condition:
  - The effect of a diameter cap was negligible.
  - Tree groups and openings were effectively created in the diameter cap treatment.
  - The difference in foliar biomass (a metric positively linked to crown fire behavior) between the treatment types was negligible.
- Where the current conditions was comprised of a relatively high number of trees greater than 16 inches in diameter:
  - The diameter cap treatment retained an additional 28 trees/acre (69 trees/ha) compared to the no-cap treatment.
  - It was problematic to establish canopy gaps and retain tree groups necessary for an uneven-aged forest management prescription.
  - Foliar biomass was significantly higher in the cap-constrained treatment versus the no-cap treatment (51 percent vs. 21 percent).

Abella et al. (2006) also caution about assessing the effects of a diameter cap based on conditions immediately after treatment. The cap may respond to certain short-term management objectives of fuel reduction or large tree retention, but the cap essentially sets a minimum tree density, basal area, and canopy biomass, and limits the developmental dynamics typical of this forest ecosystem. The residual trees will continue growing and increasing biomass, canopy closure, and fire risk.

An unpublished study by Higgins (2011) has also challenged the notion that large trees have become rare in the Southwest. In an assessment of historic inventory data from the Kaibab National Forest and other forests in northern Arizona, Higgins compared contemporary and historic conditions in ponderosa pine forests. He determined that all ranger districts on the Kaibab have a greater number of trees 16 inches in diameter and larger than they did historically, based upon inventories reported in Woolsey (1911) and Lang and Stewart (1910). It's only at larger tree diameters that current and historic tree densities are approximately equivalent—20 inches on the Tusayan district, 22 inches on the Williams district, and over 24 inches on the North Kaibab Ranger District. Higgins' study included a similar assessment of conditions across broader scales in northern and central Arizona that are indicative of the region (figure 1). In this assessment, the current average and maximum density of trees 16 inches and over was compared with historic conditions as interpreted from Woolsey and Lang and Stewart.

Figure 1 suggests that the density of large trees, 16 inches and greater, has increased in recent decades compared to historic conditions. Though the density of large trees has increased, the overall proportion of large trees today has decreased with fire suppression and the increasing abundance of small trees. The historic stands of maximum density ("Max") reflect the efforts of early inventory crews charged with deliberately locating and measuring those stands with the highest densities of large trees. Today's large tree density in northern Arizona is greater than historic in all but the densest stands located in the early 1900s. This assessment does not account for spatial variation, and it's likely that the spatial distribution of large trees is more homogenous than it was historically. Under a diameter cap scenario, the proportion of large trees continues to increase with each thinning treatment that targets only small trees. Figures 2 and 3 display similar trends but on a regional basis for the Southwest.

Study Objectives

The current study seeks to supplement the work of Abella and others, including Fiedler et al. (2002), who have explored diameter cap strategies and related issues. With this study, we expand the scope of the evaluation of a diameter cap to include extended model simulations and additional empirics and model calibration for the analysis of structure.

A 16-inch diameter cap has been suggested, either specifically or in practical effect, as a programmatic approach to restoring forest systems that are at moderate to high risk of stand-replacing fire, as a management theme in forest plan revision processes currently underway in the region. This study represents an effort to compile, develop, and report available science on the effects of a diameter cap to achieving and maintaining desired conditions within uneven-aged forest ecosystems. We've documented the results of Vegetation Dynamics Development Tool (VDDT) (ESSA 2006) and Forest Vegetation Simulator (FVS) modeling (Dixon 2002), testing the effects of a programmatic application of a 16-inch diameter cap on management for desired conditions in ponderosa pine and dry mixed conifer types. This manuscript is based in large part on methodology recently developed to calibrate VDDT models using FVS (Weisz et al. 2010). We did not examine site-specific circumstances where application of a prescription incorporating a diameter cap may meet project objectives. Rather the study is focused on the effects of a diameter cap on achieving or maintaining desired conditions at the programmatic level, at the scale of national forests.

For the purposes of this analysis and discussion, three primary elements are considered to determine whether management strategies move conditions toward or away from desired conditions: (1) forest structure (age/size class distribution, density, spatial arrangement), (2) forest composition (species), and (3) ecological function (fire behavior).

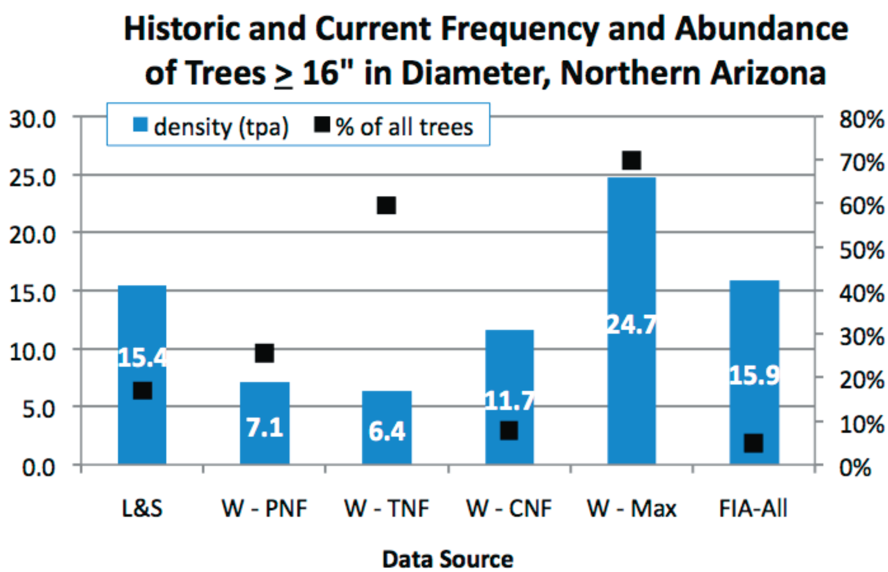
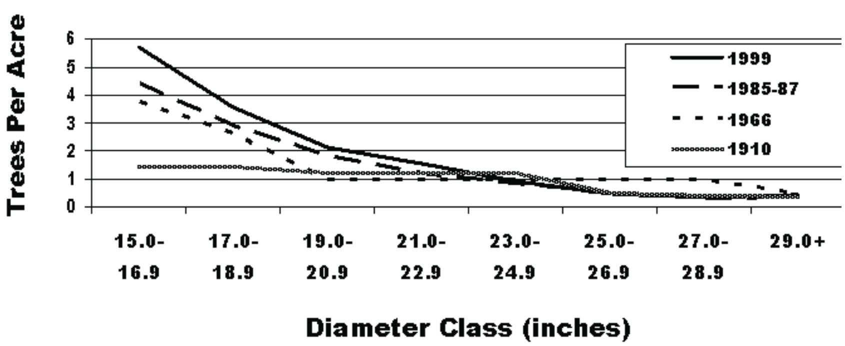


Figure 1. Current average and maximum density of trees ≥ 16 inches compared with historic conditions as interpreted from Woolsey (W) (1911) and Lang and Stewart (L&S) (1910). The proportion of all trees that is made up of those 16 inches and greater is also included. Historic data sources represent the Prescott NF (PNF), Tusayan NF (TNF) (now part of the Kaibab NF), and Coconino NF (CNF). "Max" reflects the densest stands located during the early 1900s inventories. Current conditions are represented by FIA (FIA-All) across the same region of north-central Arizona.

Figure 2. Tree density by size class for ponderosa pine forest types on nonreserve forest lands of national forests in Arizona and New Mexico, by inventory period.



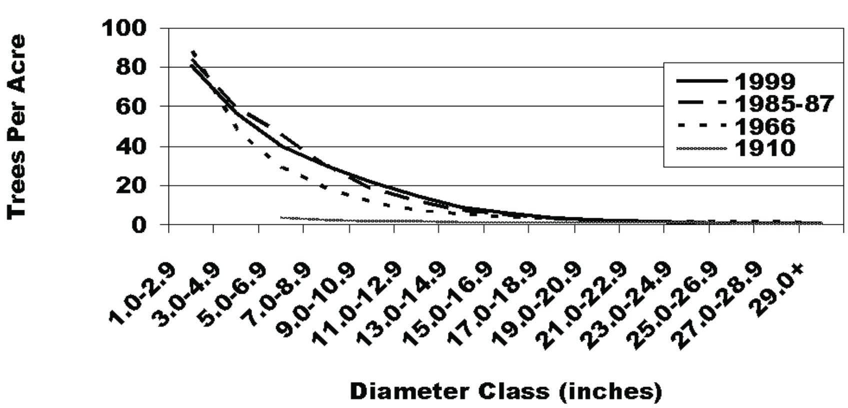


Figure 3. Density of trees 15 inches in diameter and greater, for the ponderosa pine types on nonreserve forest lands of national forests in Arizona and New Mexico, by inventory period.

Methods

Study Area

Our analysis was focused on the dry forest systems of the USFS Southwestern Region, as they occur on Forest Service lands of Arizona and New Mexico. All Forest Service lands have been mapped by PNVT, and the analysis specifically considered the ponderosa pine/grassland, ponderosa pine/Gambel oak, and dry mixed conifer PNVTs as represented by a probability sample of vegetation across these systems (see "Data"). Descriptions for these systems are included in the introduction. The analysis focused on actively managed lands.

Data

Data for the modeling analysis were derived from the Forest Inventory Analysis (FIA) Program. The FIA established a systematic vegetation inventory where data are periodically gathered on permanent plots from all forested lands across the United States (U.S. Code 1998; 16 USC § 1642). Plots are randomly located on a sample design with approximately 5,000 meters between plots, and the exact plot locations are kept secret to prevent bias. Plots that occur on national forests in Arizona and New Mexico in PPG, PPO, and DMC were used as statistical samples for modeling with the Forest Vegetation Simulator (FVS) (see "FVS Modeling"). All plot data were used to calibrate natural growth in the absence of disturbance, while finer subsets were used to calibrate the effects of specific management activities (Moeur 2011). The FVS model is a well established stand simulator program (Dixon 2002) used to project stand growth over time under the influences of site productivity, natural disturbance, and silviculture. A detailed process of sample data compilation and synthesis, over several steps (Weisz et al. 2011), was required to stratify and prepare FIA tree list data sufficient to enable FVS model projections and the analysis of a diameter cap scenario.

Stratification within Ecosystems

Both the ponderosa pine and dry mixed conifer systems have been stratified by ecosystem states of specific combinations of size, cover, canopy layering, and dominance type (Triepke et al. 2005). State and transition models have been built for each major ecosystem of the Southwest using the Vegetation Dynamics Development Tool (VDDT), a landscape analysis software developed to project vegetation conditions over time (Weisz et al. 2009). Each VDDT state represents an important phase in the ecosystem dynamics of a PNVT, either in terms of ecological processes or management themes. Table 1 summarizes the ecosystem states and their differentiating criteria for the ponderosa pine and dry mixed conifer systems. For each of the three PNVTs, FIA samples were respectively assigned to the appropriate model state (table 1), and then grouped with similar strata (table 2). Grouping by similar strata ensured the larger sample

Table 1. Stratification of ponderosa pine and dry mixed conifer states A through M, according to key attributes of canopy layering, canopy cover, and predominant tree diameter

Canopy Layering	Canopy Cover	GFB-SHR[1]	Tree Diameter[2]			
			0-5"	5-10"	10-20"	20"+
Single	Open[3]	A, N[4]	B	C	D	E
Single	Closed[3]		F	G	H	I
Multi	Open				J[5]	K[5]
Multi	Closed				L	M

[1] GFB-SHR – Plant communities with ≤10 percent tree canopy cover, dominated by grass, forb, or shrub species.

[2] Tree diameter classes determined by the size class (0–5", 5–10", 10–20", 20"+) with a plurality of basal area.

[3] Tree canopy cover classes include "open" (10–29.9 percent) or "closed" (≥30 percent).

[4] There are two grass-forb-shrub states differentiated by successional sequence, where state A represents the historic trajectory of reforestation following localized disturbance, and state N represents a static, uncharacteristic state with little or no tree regeneration following stand-replacing fire on contemporary landscapes.

[5] Desired condition, open multilayered (representing young, mid, and old trees), average diameter varying by site productivity

Table 2. FIA sample plot numbers and proportion for each model stratum of the PPG, PPO, and DMC PNVTs

Model Stratum	PPG		PPO		DMC		Total	
	n	Percent	n	Percent	n	Percent	n	Percent
JKLM	84	30	48	33	91	48	223	33
DEHI	97	35	38	26	29	15	223	33
CG	57	21	46	32	42	22	145	22
ABF	40	14	14	10	28	15	82	12
Total	278	100	146	100	190	100	673	100

sizes necessary for reliable model projections, while still allowing for some evaluation of variance in the outputs.

FVS Modeling

Simulations were conducted using FVS with the objective of modeling a 16-inch cap. Eighty-year simulations were used with successive prescribed cutting treatments to achieve and maintain 60 ft^2/ac of tree basal area, but with an overriding retention of all trees 16 inches and above in diameter. A value of 60 ft^2/ac is near the middle of the desired range of 30–80 ft^2/ac (7–18 m^2/ha) for ponderosa pine, which may be retained in this range for most of a 30-year period between scheduled treatments. For DMC, 60–80 ft^2/ac (14–18 m^2/ha) is considered a suitable range of mid-points given the greater target basal area range of 40–100 ft^2/ac (9–23 m^2/ha) for mixed conifer, but modeling results are based on 60 ft^2/ac. Accordingly, the FVS model was carefully parameterized to reflect cutting treatments designed to achieve or maintain stand densities at 60 ft^2/ac, while imposing strict retention of all trees over 16 inches. Where current stand conditions conflict with attainment of both objectives, retention of all trees greater than 16 inches in diameter was given preference over the density target for modeling the effects of this constraint. Two subsequent cuttings with the identical treatment prescriptions were scheduled in the model at 30 and 60 years following the initial treatment. Unlike other variants of FVS, the Southern Rockies variant used with this analysis does not include default imputation for tree regeneration. For parameterization of tree regeneration we followed Vandendriesche (2010), and assumptions involving stand density index are discussed in the following section, "Species Composition in Dry Mixed Conifer."

The FVS model is capable of reporting several stand variables to support the evaluation of silvicultural treatments and effects of stand dynamics. Averages and variance of the variables were reported for each stratum, along with values for individual plots, all computed for each decade of the simulation. The stratum averages include:

- Basal area (BA)
- Quadratic mean diameter (QMD)
- Stand density index (SDI)
- Trees per acre (TPA) by species and diameter class

The variables computed for each plot were given by the diameter classes of 0–5" (0–13 cm), 5–10" (13–25 cm), 10–20" (25-51 cm), and 20"+ (51 cm+) and include:

- BA
- TPA
- SDI

For ecological sustainability analysis in the Southwestern Region, a canopy cover threshold of 30 percent was established to differentiate open and closed forest canopies. Ecological syntheses by TNC (2006) and others have shown key differences in the fire regime and the resulting forest structure and wildlife habitat below and above this approximate value for ponderosa pine and dry mixed conifer systems. For purposes of this analysis, a basal area threshold of about 60 ft^2/ac (14 m^2/ha) is used to represent an equivalent level of forest structure to differentiate open and closed conditions by the basal area metric (Mitchell and Popovich 1996). Open states are those with basal area values less than about 60 ft^2/ac—states A, B, C, D, E, J, and K (table 1). Closed states—F, G, H, I, L, and M—are states with at least 60 ft^2/ac of basal area. Note that the PNVTs evaluated with this study share the same naming convention for their respective model states.

The FVS also provides both age diversity and canopy layering, or storiedness, as a means to evaluate the uneven-agedness of a stand. Given the positive relationships of tree size and diameter, storiedness gives a useful inference of age diversity that is apparent. Storiedness is also one of the primary differentia of ecosystem states (table 1), and a key characteristic of these ecosystems, where uneven-aged and multistoried conditions reflect the desired condition (states J and K). Storiedness was reported, along with the variables listed above, immediately preceding the initial cutting treatment and then for every subsequent decade over the next 70 years of the simulation. The storiedness algorithm used in our analysis was used as an inference of tree age diversity, and is described in the following decision tree:

Is the basal area of trees that are ≥20" (51 cm) in diameter at least 20 percent greater than the basal area of trees that are ≥10" (25 cm) and <20"?

- NO – Single storied
- YES – Is the basal area of trees that are ≥20" in diameter at least 20 percent greater than the basal area of trees that are ≥0" and <10"?
    - NO – Single storied
    - YES – Multistoried

Results of FVS modeling for PPG, PPO, and DMC are reported by each decade of the 80-year simulation (table 3). The basal area and storiedness values calculated for each stratum and each decade were weighted by the number of FIA plots in each stratum, and then summarized into a percent attainment of desired conditions. Individual states within each stratum were identified by computations made for each decade according to differentiating values of basal area, storiedness, and dominant tree size range. The most frequent state was also identified for each decade and for the modeling period. These same variables were also averaged across each stratum to assess the attainment of desired conditions in each reporting year across the simulation.

Results

The FVS modeling results are summarized by the proportion of stands that meet desired conditions with a 16-inch cap strategy (table 3). Conditions listed for 2010 reflect overall stand conditions just prior to the first treatment. As mentioned, prescribed cutting treatments were repeated two more times during the simulations in years 2030 and 2060. The table includes critical attributes of basal area (BA) and multistoried (MS) conditions, where storiedness is used as an inference of age diversity. In this study, whether overall desired conditions are met is determined by whether both attributes of basal area and storiedness are met.

In an effort to provide an unbiased accounting of the effects of a diameter cap policy, model simulations were made on the assumptions that regulatory framework and the availability of resources did not limit the access and treatment to all stands. In our modeling, each suitable stand was subject to the regular cutting treatments prescribed in FVS. And in this context for a stand to be suitable it must have had merchantable trees less than 16 inches in diameter in a stand that did not meet desired conditions.

The results in table 3 show that nearly all stands were considered multistoried at the beginning of the modeling period. In all three PNVTs, the percentage of stands that meet multistoried conditions continued to decline as the proportion of trees larger than 16 inches increased across the simulation and the positive effects of treatments were negated. The loss of multistoried conditions appears to accelerate in the first half of the modeling period. By the time the third treatment is implemented, conditions in both storiedness and basal area are more or less static, unless natural disturbance creates new canopy gaps (see "Discussion"). This analysis shows that within 3 decades, all simulation stands would be converted to conditions that are functionally even-aged, given that younger cohorts do not take on diameter growth typical of uneven-aged systems due to the poor physiological conditions of trees growing under high-density forest canopies, and given the lack of tree regeneration.

Table 3. The proportion of forest ecosystems meeting desired conditions under a diameter cap policy are listed according to target ranges for basal area (BA) and multistoried (MS) conditions; results based on FVS modeling over an 80-year simulation

Year	PPO		PPG		DMC	
	BA	MS	BA	MS	BA	MS
2010[A]	14%	100%	10%	100%	15%	100%
2020	100%	35%	100%	41%	100%	100%
2030	14%	35%	10%	41%	100%	100%
2040	70%	35%	68%	41%	63%	52%
2050	35%	14%	10%	10%	100%	37%
2060	0%	14%	0%	10%	100%	37%
2070	14%	14%	10%	10%	100%	37%
2080	14%	14%	10%	10%	100%	37%

[A]Conditions prior to initial cutting treatment.

Results also show with all three PNVTs that basal area targets are achieved one decade after the initial treatment and, in the case of ponderosa pine, the percentages trend downward with time as fewer trees under 16 inches remain to present opportunities to modify stand conditions toward desired conditions. On the other hand, dry mixed conifer affords the ability to achieve basal area targets at least as reflected in the beginning 80 years of the management scenario, but with an increasing plurality of shade tolerant conifer species (see "Discussion"). In part this is due to differences in site types in mixed conifer that favor greater tree density and regeneration of shade tolerant species (see "Species Composition in Dry Mixed Conifer"). However, the cutting constraints can also force tradeoffs between basal area and desired species composition targets in dry mixed conifer forests (see "Discussion").

In nearly all stages of the simulations and across all three PNVTs, the inability to develop or maintain uneven-aged forest structure is the most limiting factor in achieving desired conditions. The ability to progress toward desired structure conditions is achievable through the first treatment in some stands, with overall percentages declining significantly approximately 40 years into the simulation to 14 percent, 10 percent, and 37 percent for PPG, PPO, and DMC, respectively. That multistoried conditions are achieved in DMC is enabled, in large part, by the regeneration of shade tolerant conifers, counter to the desired species composition for the PNVT (see "Discussion").

Discussion

Our analysis indicates that maintaining desired conditions for the PPG, PPO, and DMC systems is problematic with a diameter cap policy, and that achieving desired conditions where they do not exist on contemporary landscapes is even more difficult. Tree density, as determined with basal area, and age diversity, as inferred from forest canopy storiedness, were the two principle attributes used to assess consistency with the desired conditions that have been formally defined for these three systems for the USFS Southwestern Region (USDA Forest Service 2010). In large measure, basal area and storiedness alone can be used for evaluation. In DMC, the composition of tree species is another primary consideration (Arno and Fiedler 2005).

Analysis by FVS suggests that desired conditions for basal area in ponderosa pine, 30–80 ft^2/ac, cannot be maintained over time and even in the short term can only be met on a minor percentage of the area. Examination of individual FIA samples tells us that in some cases where desired conditions have been met, too few large trees exist in the first place so that a diameter cap is irrelevant, and the "diameter cap" label does not fit the true silvicultural method. That only the mid-point of the target range was considered for modeling suggests that the likelihood of achieving lower values of the range, even more indicative of historic conditions, would be that much more difficult on a programmatic scale. And even when desired conditions are met for basal area, a much smaller minority of stands meet age diversity targets in most instances. Meeting composition targets in DMC is also unlikely (see "Species Composition in Dry Mixed Conifer").

At the beginning of the simulation nearly all stands were considered multistoried, suggesting that the algorithm used is very liberal in making the assignment—i.e., the stand is more likely to meet desired conditions by this algorithm. The current algorithm represents only a 2-class system, versus a 3-plus story system indicative of true uneven-aged conditions. The storiedness algorithm is being refined for the Southwestern Region to reflect a 3-class system to reflect forest plant communities that are truly uneven-aged.

Following implementation of a 16-inch cap, the percentage of stands that meet uneven-aged conditions declined precipitously due to the preservation of all large trees representing the upper cohorts, treatment tradeoffs between stand structural diversity and basal area targets, and the simultaneous reduction in opportunities for tree regeneration necessary to sustain the recruitment essential for an uneven-aged/diameter distribution within the plant community. Imposing diameter caps in managed density stands most often results in the elimination of small- and mid-sized diameter trees, due to the tradeoff forced between achievement of stand structure and density targets.

As expected, the manager can ostensibly progress toward desired conditions with diameter constraint following the initial entry on a minor percentage of the landscape; but, the effects of the harvest are short term so that the percentage moving toward desired conditions is reduced to less than half of the peak overall percentages only 40 years into the projection (table 3). Despite the immediate pulse in stands progressing toward desired density conditions, even a temporary diameter cap policy has a long-term liability on opportunities to manage for (implement or maintain) uneven-aged forest structure. All else equal, maintaining a diameter cap policy for even a short term reduces the number of stands suitable for treatment to achieve uneven-aged conditions, given the lost opportunities for ensuring continual tree regeneration and age diversity that an increasingly dense single-storied component of 16" plus trees forestalls. Growth rate is likewise affected. Forty years of sample data from the Taylor Woods study, at Fort Valley Experimental Forest in northern Arizona, show that, for example, a 12-inch tree (30 cm) will attain a 16 to 18 inch diameter in about a decade at a rate of disturbance commensurate with pre-European settlement disturbance regimes (Bailey 2008). Trees in lower density conditions grew significantly faster in diameter, crown length, and crown width; that is, the smaller size of younger cohorts is temporary as long as competition is sufficiently controlled by silvicultural treatments or other disturbance.

As mentioned, the FVS simulations in this study were conducted under the assumption that forest managers would have resources to consider treatment in all stands, without regulatory hindrance, to reduce complicating factors in the analysis. In reality, resources, regulation, and policy will substantially limit the manager's ability to restore and maintain desired conditions on a broad scale. Results by this study suggest that the effects of a diameter cap policy would be further exacerbated by these limitations, given that managers will tend to focus their energy on the limited opportunities where the economics support harvest activities or where stand conditions favor successful outcomes. In these cases the likelihood of achieving desired conditions over the long term are reversed by a policy that incidentally favors dense single-storied forest conditions. The remainder of untreated stands will tend to average higher densities with time (see table 3, 2010 conditions).

Collateral effects of a diameter cap policy in PPG, PPO, and DMC involve changes in fire risk and habitat diversity associated with changing fire regimes and, in DMC, significant shifts toward shade tolerant, fire intolerant species of conifers, which impact long-term sustainability. The composition shifts also reduce biodiversity and key wildlife habitat components such as shade intolerant hardwood species, including aspen and oak.

Effects of Stand Density

Stand level characteristics for desired conditions of PPG, PPO, and DMC have also been qualitatively described (see appendix A), and include spatial arrangement for trees within the plant community subject to local circumstances. Desired conditions for all three PNVTs specify an arrangement of trees into clusters or groups of one to many trees, some with high density, surrounded by openings of sparse tree cover that are dominated by grasses or shrubs (depending on the particular plant association). Under a diameter-cap policy, the characteristic spatial arrangement of trees in many areas is becoming increasingly difficult to attain as former openings regenerate, many now with trees over 16 inches in diameter (Moore et al. 2004). Also, since no trees over 16 inches would be cut to reach density objectives, the pressure to harvest more or all trees under 16 inches is likely to result in more homogenous structure, as trees under 16 inches are targeted to achieve the desired conditions for basal area. Regular interspersion of tree groups of differing ages is likewise important for biodiversity:

- According to Reynolds and others (1992), high interspersion is of moderate to high value for 11 of 14 goshawk prey species. The authors also report that an herb-shrub component characteristic of forest gaps is important for a separate set of 11 prey species. The limitations of diameter cap management are likely to inhibit tree group interspersion and the sustenance of an understory with characteristic composition.
- Reductions in overstory density to more heterogeneous patterns of openings among trees groups of moderate density levels are commensurate with objectives to increase understory plant diversity (Griffis et al. 2001, Laughlin et al. 2006, Moore and Dieter 1992).
- Even moderately dense tree cover reduces native plant abundance (Griffis et al. 2001, Sabo et al. 2008) and diversity (Bataineh et al. 2006)(Laughlin et al. 2004).

Similar studies on and near the Kaibab National Forest in northern Arizona show a strong correlation between overstory density and understory species diversity and production (Abella 2009, Bataineh et al. 2006, Moore and Deiter 1992). Deiter (1989) showed that the basal area of trees must be below about 65 ft^2/ac (36 m^2/ha) to produce a robust understory response, defined as at least 50 percent of site potential.

In DMC, as forests become denser under a diameter-cap policy, their ability to regenerate ponderosa pine sustainably is frustrated by the regeneration of shade tolerant conifers favored under scenarios of limited and infrequent disturbance (Heinlein et al. 2005) (see "Species Composition in Dry Mixed Conifer"). Though intervention is still necessary to control the growth of shade tolerants, canopy gaps facilitate the regeneration of ponderosa pine, the development and maintenance of uneven-aged forest structure, and the diversity and abundance of understory vegetation.

In summary, stand density provides strong inference for ecosystem dynamics and associated structure and habitat characteristics. Irregular forest density, for instance with canopy gaps and nonforest openings, can facilitate the reintroduction and maintenance by frequent surface fire and allow land managers more control over fire (Pollet and Omi 2002). This type of forest structure can also limit the transition of surface fire to crown fire during severe burning conditions, reducing the probability of uncharacteristically severe fire effects (DeBano et al. 1998, Scott 2003). The restoration of historic forest spatial patterns, including canopy gaps and tree groups, is critical to proper ecosystem function and related biodiversity.

Table 4. Standard management activities evaluated using FVS, as represented by FIA samples across dry mixed conifer forests of the Southwest

Code	Management Activity
B	Free thin, all sizes to target basal area, 50 ft^2/ac (11 m^2/ha)
C	Thin from below to target basal area, 80 ft^2/ac (18 m^2/ha)
D	Thin under a 16-inch diameter cap to target basal area, 60 ft^2/ac (14 m^2/ha)
E	Group selection with matrix thin to target basal area, 70 ft^2/ac (16 m^2/ha)
F	Shelterwood seed cut to target basal area, 30 ft^2/ac (7 m^2/ha)
J	Prescribed fire, low intensity burning conditions
K	Prescribed fire, moderate intensity burning conditions
L	Prescribed fire, high intensity burning conditions
M	Thin under a 9-inch diameter cap, 150 ft^2/ac (34 m^2/ha)

Species Composition in Dry Mixed Conifer

The composition of tree species in dry mixed conifer forests is of particular interest to forest managers in the West (Arno and Fiedler 2005, North et al. 2009), and adds an important restoration component equal to tree density and vertical stratification. For analysis on the effects of a diameter cap on the restoration and maintenance of forest composition in DMC, we turn to related work by Moeur (2011) and to key concepts of stand density index (SDI).

First, in her recent analysis Moeur (2011) modeled changes in tree species composition in dry mixed conifer systems as the result of a standard set of management activities (table 4). Each management activity was evaluated by simulating silvicultural and fuels treatment prescriptions with FVS, using subsets of FIA plots associated with each VDDT model state. The FIA tree list data were compiled from samples occurring in DMC forests across USFS lands of the Southwest. Simulations were generated for each management theme, the results analyzed according to the effects by management on structure and composition.

Using white fir as a key successional indicator, results are summarized in figure 4 for all management activities. White fir has low resistance to fire, is shade tolerant (Burns and Honkala 1990), and is favored by infrequent fire and closed canopy conditions. Historically it was a subordinate component in DMC (as with desired conditions) and is now much more abundant, due primarily to fire suppression and the capacity of white fir to thrive in high stem densities (see following discussion on stand density index). Figure 4 shows the considerable disparity in the density of large white fir trees between the 16-inch diameter cap and uneven-aged management treatments. After one treatment, the density of white fir in the diameter cap scenario is about three times that of the group selection immediately following treatment. The diameter cap scenario points to the inability of managers to meaningfully affect composition of the residual stand.

This assessment provides an example of how a shade tolerant species is retained in higher than desired proportions relative to desired conditions as a result of the cutting constraint. This analysis does not examine species composition of tree species regeneration following treatment, and the subsequent cumulating effects on stand composition. Large white fir and other undesired species that are retained by this cutting constraint become seed trees that perpetuate shade tolerant species and jeopardize true restoration objectives. Stand density index can be used to show that diameter cutting constraints are likely to result in profound shifts in tree species composition over time, favoring the regeneration and sustenance of shade tolerant and fire intolerant species.

The stand density index (SDI[1]) is a conceptual framework that relates an absolute density measure to forest stand developmental dynamics (detailed discussion in appendix B). The SDI provides a long accepted, operational methodology for stand dynamics. Long (1985) divided the stand density index into four zones based on the percent of the overall density of a tree stand relative to the biological maximum density, a species-specific value. Table 5 displays the four zones, and includes descriptions of the dynamics of tree regeneration establishment, competition, and growth based on stand density percentages relative to the maximum SDI values specified for each tree species.

The stratification of stand density index in table 5 provides a useful means for discussing stand dynamics relative to species composition, and the implications of varying the timing, scale, and intensity of density management to affect the variety of stand and tree characteristics (Long 1985, Long et al. 2004, Shaw and Long 2010):

- Regeneration of desired species can be initiated by maintaining stand density in zone 1, based on maximum SDI of desired species. The regeneration model utilized in FVS was based on this assumption (see "Methods").
- Open canopy stands with grassy understories and large diameter trees with long, heavy-limbed crowns can be developed by targeting densities in zones 1 and 2.
- Stands of moderate crown closure and intermediate sized trees with thrifty, well-pruned crowns can be

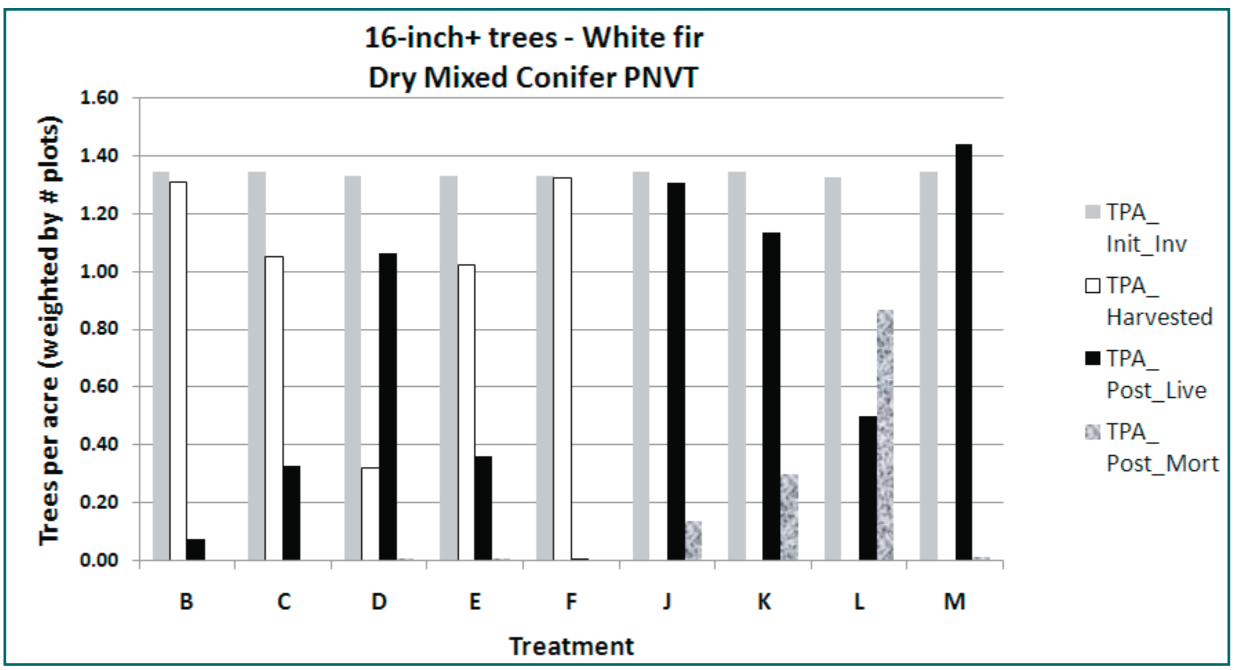


Figure 4. Large white fir tree density (TPA) immediately before and after each management treatment scenario (table 4) simulated by FVS, as an indication of successional status and consistency with desired conditions (where white fir is subordinate).

[1] Measure of stand density in relationship to number of trees in a stand to quadratic mean diameter expressed as a percentage of the maximum (SAF 1998).

Table 5. Percent of maximum SDI (Langsaeter 1941) by density zone according to key stand dynamics (Long 1985)

Percent Maximum SDI*	Zone	Stand and Tree Characteristics
0–24 percent Low density	1	—Less than full site occupancy, maximum understory forage production. —No competition between trees, little crown differentiation. —Maximum individual tree diameter and volume growth. —Minimum whole stand volume growth. —Tree regeneration freely establishes.
25–34 percent Moderate density	2	—Less than full site occupancy, intermediate forage production. —Onset of competition among trees, onset of crown differentiation. —Intermediate individual tree diameter and volume growth. —Intermediate whole stand volume growth.
35–60 percent High density	3	—Full site occupancy, minimum forage production. —Active competition among trees, active crown differentiation. —Declining individual tree diameter and volume growth. —Maximum whole stand volume growth. —Upper range of zone marks the threshold for the onset of density-related mortality.
>60 percent Extremely high density	4	—Full site occupancy, minimum forage production. —Severe competition among trees, active competition induced mortality. —Minimum individual tree diameter and volume growth, stagnation. —Declining whole stand volume growth due to mortality

Percentages based upon individual species (Shaw and Long 2011). Examples include ponderosa pine maximum SDI = 450, Douglas-fir maximum SDI = 570, and white fir maximum SDI = 640. Note that the absolute density measure is calculated for the entire stand, but that developmental characteristics differ for each species within the stand based on the established maximum density for the species.

developed by targeting densities in the upper half of zone 2 and the lower half of zone 3.

- Clumpy, irregular stands containing groups of varying ages can be developed through periodic creation of canopy openings (zone 1), where growing space for tree regeneration is made available for seedling establishment.
- Longevity of existing large diameter trees could be enhanced by thinning adjacent smaller trees to create zone 2 or 3 growing conditions.
- Avoiding density related mortality and maintaining forest vigor can be achieved by maintaining densities at or less than the lower half of zone 3.

By considering SDI with these management strategies, stand density can be modified to favor the regeneration of shade intolerant conifers in dry mixed conifer, as a means of achieving desired conditions.

Fire Behavior

While fire risk and postfire effects associated with high density forests in the western U.S. are well established, little is known about the direct responses of fire behavior to a diameter cap. What diameter cap treatments have been implemented in the Southwestern Region have occurred at project scales and only within the last 10 years so that observations on the potential impacts to fire behavior and resulting fire regimes are problematic. An unpublished study by Nicolet (2011) was recently conducted on the Apache-Sitgreaves National Forests in Arizona, and considered the effects of a 16-inch cap on forest ecosystems including the potential for passive and active crown fire. The study was part of an environmental analysis to evaluate the effects of the proposed Rim Lakes Forest Restoration Project. In this study, the potential fire behavior was modeled for a range of management alternatives with the following assumptions:

- No action – No management other than fire suppression.
- Uneven-aged forest management – Areas outside of Mexican spotted owl habitat managed for large trees and the northern goshawk by implementing combinations of group selection cuttings to spatially distribute forest age classes and canopy openings. Mechanical treatments are followed with prescribed fire. Slash created from tree harvest is piled and burned, or lopped and scattered and burned. Broadcast burns are applied on a 2- to 15-year return interval over time in ponderosa pine forest types and 5 to 25 years in dry mixed conifer forest types.
- 16-inch diameter cap – The analysis area is managed as with the uneven-aged alternative, but cutting is limited to trees less than 16 inches in diameter. To the extent possible, similar spatial distribution of age classes is promoted, though the cutting constraint resulted in different outcomes. The two alternatives were similar in all other ways.

Potential fire behavior was modeled using FVS and the Fire and Fuels Extension (Reinhardt and Crookston 2003) and the FLAMMAP model (Finney 2006). Results assume that the time since treatment allowed for the recovery of fine fuels in treated areas, 2 to 4 years post treatment. Analysis results are reported in table 6.

Crown fire would be expected over about two thirds of the analysis area as a result of the "no action" scenario (23 percent active, 44 percent passive), suggesting higher tree mortality in a given fire event compared to the other two management alternatives. Results for the uneven-aged alternative showed a significant reduction in passive crown fire compared to the no action alternative (16 percent vs 44 percent), inferring reduced tree mortality and impacts to forest structure. The 16-inch cap alternative also exhibited a reduction in passive crown fire, but still had nearly double the potential for passive crown fire compared to uneven-aged management.

As with our analysis of basal area, the effects of diameter cap cutting are deceptively short lived (Abella et al. 2006). There are likewise implications for fire behavior, not only in the false sense of hazardous fuels reduction that such treatments provide for the longer term, but in the way such stands are modified to make restoration more difficult. The removal of one or more tree age class cohorts may require many decades to replace through recruitment and growth. The analyses reported here indicate that a diameter cap substantially effects stand structure, species composition, and ecological function, to constrain future management options and to lengthen the time necessary to achieve desired conditions.

Economics

A diameter cap comes at a lower cost efficiency that, in turn, may impact the rate of restoration for a given administrative unit. Restoration treatments often cost more to implement than the value of the products produced by them—in a range of about $300 to $730 per acre ($740 to $1,800/ha) for cutting alone, and a

Table 6. Projected fire behavior within the Rim Lakes study area as a proportion of the project area resulting from each alternative—no action, uneven-aged management, and 16-inch diameter cap.

Fire Behavior	No Action	Uneven-aged	16-Inch Cap
No Fire	1%	1%	1%
Surface Fire	32%	66%	51%
Passive Crown Fire	44%	16%	30%
Active Crown Fire	23%	17%	18%

cost of around $830 per acre ($2,050/ha) for associated fuels treatments and administrative costs (Hjerpe et al. 2009). Diameter caps affect the profitability of restoration projects, according to the merchantability of trees less than 16 inches, usually subordinate and codominants with inferior quality, and by the limit on the amount of wood that such a limit indirectly imposes. Larson and Mirth (2001) found that a "cap resulted in implementation cost increases of 5 to 19.4 percent, harvested fiber decreases of 10 to 39 percent on a volume basis, and reductions in operator net returns ranging from 22.3 to 176 percent. And this doesn't account for treatment longevity in relation to fuels and other restoration objectives. Even if the cost to implement diameter cap and uneven-aged treatments were equal, our analysis suggests that a more evenly distributed canopy (less gaps) resulting from a cap will close after the first decade or so, as opposed to uneven-aged management with irregular stand density (and gaps) that closes after 20 to 30 years. As a result, stands treated with a cap will require more frequent entries, as long as treatments are viable, leading to higher service costs.

Because Federal budgets are relatively limited, projects that require subsidies are also limited, and competition for available funding may well increase as other areas in the West seek to undertake large-scale restoration projects (USDA Forest Service 2011, WGA 2001). Even with a long-term contract in place, such as the White Mountain Stewardship Project (Sitko and Hurteau 2010), a taxpayer subsidy of about $480 per acre ($1,240/ha) is required (pers. comm.. Paul Fink, White Mountain Stewardship Project forester). With other factors being equal, lower costs to restore forests can translate to more acres restored in a given time period.

Conclusion

Fire-adapted forest systems were historically driven by frequent fire burning through an herbaceous understory to maintain open, uneven-aged conditions in ponderosa pine and dry mixed conifer forests of the Southwest. Restoration treatments on today's landscapes are used to lower the overstory density and canopy continuity and reestablish forest openings to provide for recruitment of younger tree cohorts sufficient to reestablish these conditions and prevent uncharacteristic fire effects. Ultimately, the goals of restoration are to provide ecosystem function, including plants and animal habitat, largely as a byproduct of providing for economic and social benefits including lower fire risk to surrounding communities. The results of this study discredit the efficacy of thinning treatments under a preservation strategy that imposes diameter caps, and the sustainability of such a policy given that:

- The plurality of stands would trend toward a large diameter, single story, closed-canopy condition;
- Closed canopy forest stands do not allow for the sustainable growth of shade intolerant (fire resistant) tree species into the future (not to mention continued recruitment for the large diameter trees of the future);
- Closed canopy forest stands do not provide canopy gaps to support robust understory vegetation for plant diversity and wildlife habitat;
- In dry mixed conifer forests, a diameter cap favors the retention and regeneration of uncharacteristic proportions of shade tolerant, non-fire resistant conifer species;
- Without openings and canopy gaps, closed canopy, single-storied forest stands are more susceptible to crown fires and changes to fire regimes, along with long-term conversion of forested plant communities to shrub- and herb-dominated vegetation types (Savage and Mast 2005); and
- Subsidies are required that reduce the cost efficiency of forest management, and limit the amount of area that can be ultimately treated.

This analysis shows that within 3 decades, nearly all stands managed under the constraints of a cutting size cap would be converted to a functional even-aged condition. This level of landscape-scale homogeneity lacks biological diversity, and indicates an unstable ecosystem subject to synchronous large-scale disturbances.

Where diameter caps are applied, the continued growth of residual trees following treatments will favor greater tree densities and basal area, increased homogeneity of structure, and higher frequencies of uncharacteristic crown fires. If a diameter cap is considered for political or social reasons, then it should be prescriptive and not programmatic—narrowly focused, to achieve specific local objectives. Such treatments should be followed with deliberate long-term monitoring to enable the assessment and reporting of effects. Our results also suggest that a diameter cap would limit future flexibility in management in terms of the narrowing range in conditions of forest structure and composition.

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Appendix A: Desired Conditions for Ponderosa Pine and Dry Mixed Conifer (Mixed Conifer - Frequent Fire) Systems of the U.S. Forest Service Southwestern Region

Overview (USDA Forest Service 2010)

As outlined in the provisions of the 1982 Planning Rule, desired conditions are descriptions of goals to be achieved at some time in the future. They are normally expressed in broad general terms and are timeless in that they have no specific date by which they are to be completed. Goals and desired conditions are the focus of the plan and are the basis for developing objectives and other plan components. Desired conditions, together with the other plan components, constitute a framework for sustainability and should clearly articulate management intent over the life of the forest plan.

Tabled Desired Conditions

The following tables provide quantitative desired condition values for seral stages of major ecosystems of the Southwestern Region. Seral stages are defined by model states developed with the Vegetation Dynamics Development Tool (VDDT) (ESSA 2006) software used to simulate ecosystem dynamics. The seral stage proportions are a standard expression of the narratives from the R3 Vegetation Desired Conditions Working Group, and reflect the approximate mid-points of the ranges, as described but not quantified in the narratives. Only desired conditions for forest and woodland systems have been identified at this time. Reference conditions can be assumed for the remainder of systems.

The tabled seral stage values are used primarily as a performance measure for modeling management scenarios in VDDT, and as a starting point for modifications based on local circumstances. For instance, the R3 desired conditions state for ponderosa pine forest: "Denser tree conditions exist in some locations such as north-facing slopes and canyon bottoms." Since the proportion of acres on north-facing slopes and canyons varies from one forest to the next, desired conditions may also vary so that modifications by individual forests may be necessary to reflect their local conditions. The proportion in each seral stage (model state) would be described in terms of the actual desired conditions and not in terms of management strategies and limitations. Desired condition values are updated in the accompanying tables, which are also used for area-weighting subtypes of some ecosystems. For example, on each forest, seral stage conditions for ponderosa pine forest are determined by weighting desired conditions for the ponderosa pine/Gambel oak and the ponderosa pine/bunchgrass subtypes, according to the amount of area within each subtype. The desired condition for ponderosa pine forest may, in effect, be specific for each forest according to their ratio of subtypes.

In phase II analysis of forest plan revision, desired condition values are enumerated as targets to shoot for and to be measured against. The objective of phase II modeling is to project and evaluate how conditions change over time under each management scenario. Each alternative is evaluated quantitatively, and compared among alternative management scenarios in terms of the numerical indicators of desired conditions. So, beginning with current conditions, alternative management themes are represented in VDDT. Each management theme has a unique combination of plan components such as plan objectives (which identify management actions), special areas, standards and guidelines (which put limitations on the use of management actions), and management opportunities (e.g., percent area in MSO PACs) that can vary in amount and timing. The end result of model simulations is the degree to which desired conditions are apparently achieved, usually measured in terms of a similarity index. If conditions are not trending toward the desired conditions from where they are now, either the plan alternative strategy or the desired conditions need to be modified. And, even if conditions are trending toward desired conditions, a given management scenario may be further refined to accelerate the trend.

Seral stage proportions for modeled states should be assessed only at landscape scales of 6th-code HUC units and greater, depending on the ecosystem. Applying seral stage values for spruce-fir forests, for instance, that typically have long stand replacement intervals and large patch dynamics, may only be appropriate at subregional scales. A landscape perspective may not be appropriate for certain standards and guidelines and regulatory requirements, where seral stages are sometimes assessed only at the scale of the planning unit (e.g., for MSO habitat requirements).

The following tables are accompanied by abstracts from the R3 desired condition narratives.

Ponderosa Pine Forest

Current Trends Model				Baseline Desired Conditions					
				Ponderosa Pine/Gambel Oak		Ponderosa Pine/ Bunchgrass		Ponderosa Pine Forest - All (PPO/PPG)	
Source	State	Description		S Stage	Description	S Stage	Description	S Stage	Description
USFS R3 Model PPF	A, N	GFB/SHR	=	0%	Reference condition	0%	Reference condition	0%	*Reference condition
	B	SSO	=	2%	*Conditions indicative of occasional even-aged stand dynamics and the development of MSO habitat.	1%	*Conditions indicative of occasional even-aged stand dynamics and the development of northern goshawk nesting habitat.	1.5%	*Conditions indicative of occasional even-aged stand dynamics and the development of closed mature forest habitat.
	F	SSC	=						
	C	SMO	=	2%	*Conditions indicative of occasional even-aged stand dynamics and the development of MSO habitat.	1%	*Conditions indicative of occasional even-aged stand dynamics and the development of northern goshawk nesting habitat.	1.5%	*Conditions indicative of occasional even-aged stand dynamics and the development of closed mature forest habitat.
	D, J	MOS, MOM	=	79% (Primarily as J and K)	**Based on reference condition, and the predominance of uneven-aged dynamics and open forest. The plurality of stands on low-productivity sites likely to occur as state J, versus high-productivity sites where state K is more likely.	94% (Primarily in J and K)	Based on reference condition, and the predominance of uneven-aged dynamics and open forest. The plurality of stands on low-productivity sites likely to occur as state J, versus high-productivity sites where state K is more likely.	86.5% (Primarily in J and K)	Based on reference condition, and the predominance of uneven-aged dynamics and open forest. The plurality of stands on low-productivity sites likely to occur as state J, versus high-productivity sites where state K is more likely.
	E, K	VOS, VOM	=						
Contemporary landscapes only									
USFS R3 Model PPF	G	SMC	=	2%	*Conditions indicative of occasional even-aged stand dynamics and the development of MSO habitat.	1%	*Conditions indicative of occasional even-aged stand dynamics and the development of northern goshawk nesting habitat.	1.5%	*Conditions indicative of occasional even-aged stand dynamics and the development of closed mature forest habitat.
	H, L	MCS, MCM	=	15%	Conditions indicative of MSO habitat, and occasional even-aged dynamics that occurred in the reference condition (Romme et al. 2010), particularly on north-facing slopes and canyons. The plurality of stands on low-productivity sites likely to occur as state H/L, versus high-productivity sites where state I/M is more likely.	3%	Conditions indicative of northern goshawk nesting habitat, and occasional even-aged dynamics that occurred in the reference condition (Romme et al. 2010), particularly on north-facing slopes and canyons. The plurality of stands on low-productivity sites likely to occur as state H/L, versus high-productivity sites where state I/M is more likely.	9%	Conditions indicative of mature closed forest habitat and occasional even-aged dynamics that occurred in the reference condition (Romme et al. 2010), particularly on north-facing slopes and canyons. The plurality of stands on low-productivity sites likely to occur as state H/L, versus high-productivity sites where state I/M is more likely.
	I, M	VCS, VCM	=						

* Reflects percentage of seral forests necessary to sustain at least 15 percent MSO habitat in mature closed forest.

** Based on residual proportion of the landscape not including mature closed forest (states H, L, I, M) and early-mid even-aged states (B, F, C, G).

R3 Desired Conditions (abstracted from R3 DC narratives, landscape and mid-scale)

At the landscape scale, the ponderosa pine forest vegetation community is composed of trees from structural stages ranging from young to old. Large trees are well distributed in the landscape. Forest appearance is variable but generally uneven-aged and open; occasional areas of even-aged structure are present. The forest arrangement is in individual trees, small clumps, and groups of trees interspersed within variably-sized openings of grass, forb, and shrub vegetation associations similar to historic patterns. Openings typically range from 10 percent of the total stand/state area in more productive sites to 70 percent in the less productive sites. Size, shape, number of trees per group, and number of groups per area are variable across the landscape. In the Gambel oak subtype, all sizes and ages of oak trees are present. Denser tree conditions exist in some locations such as north-facing slopes and canyon bottoms.

At the mid-scale the ponderosa pine forest vegetation community is characterized by variation in the size and number of tree groups depending on elevation, soil type, aspect, and site productivity. The more biologically productive sites contain more trees per group and more groups per area, resulting in less space between groups. Openings typically range from 10 percent in more productive sites to 70 percent in the less productive sites. Tree density within forested areas generally ranges from 20 to 80 square foot basal area per acre (5–18 m^2/ha).

The mosaic of tree groups generally comprises an uneven-aged forest with all age classes present. Infrequently patches of even-aged forest structure are present. Disturbances sustain the overall age and structural distribution.

Forest conditions in goshawk post-fledging family areas (PFAs) are similar to general forest conditions except these forests contain 10 to 20 percent higher basal area in mid-aged to old tree groups than in goshawk foraging areas and the general forest. Goshawk nest areas have forest conditions that are multiaged but are dominated by large trees with relatively dense canopies.

Dry Mixed Conifer Forest (AKA Mixed Conifer – Frequent Fire)

<table>
<tr><th colspan="3">Current Trends Model</th><th></th><th colspan="2">Baseline Desired Conditions</th></tr>
<tr><th>Source</th><th>State</th><th>Description</th><th></th><th>S Stage</th><th>Description</th></tr>
<tr><td rowspan="8">USFS R3 Model MCD</td><td>A, N</td><td>GFB/SHR</td><td>=</td><td rowspan="2">9%</td><td rowspan="2">*Reference condition and conditions indicative of even-aged stand dynamics and the development of MSO habitat.</td></tr>
<tr><td>B, F</td><td>SSC, SSO</td><td>=</td></tr>
<tr><td>C</td><td>SMO Intolerant</td><td>=</td><td>3%</td><td>**Reference condition and conditions indicative of even-aged stand dynamics and the development of MSO habitat.</td></tr>
<tr><td>D, J</td><td>MOS, MOM Intolerant</td><td>=</td><td rowspan="2">60%</td><td rowspan="2">**Based on reference condition and the predominance of uneven-aged dynamics and open forest. The plurality of stands on low-productivity sites likely to occur as state J, versus high-productivity sites where state K is more likely.</td></tr>
<tr><td>E, K</td><td>VOS, VOM Intolerant</td><td>=</td></tr>
<tr><td>G</td><td>SMC Mixed Tolerant</td><td>=</td><td>3%</td><td>**Reference condition and conditions indicative of even-aged stand dynamics and the development of MSO habitat.</td></tr>
<tr><td>H, L</td><td>MCS, MCM Mixed Tolerant</td><td>=</td><td rowspan="2">25%</td><td rowspan="2">Conditions indicative of MSO habitat and occasional even-aged dynamics that occurred in the reference condition (Romme et al. 2010), particularly on north-facing slopes and canyons. The plurality of stands of low-productivity sites likely to occur as state H/L, versus high-productivity sites where state I/M is more likely.</td></tr>
<tr><td>I, M</td><td>VCS, VCM Mixed Tolerant</td><td>=</td></tr>
</table>

* Reflects percentage of seral forests necessary to sustain at least 15 percent MSO habitat in mature closed forest.

** Based on residual proportion of the landscape not including mature closed forest (states H, L, I, M) and early-mid even-aged states (B, F, C, G).

R3 Desired Conditions (abstracted from R3 DC narratives, landscape and mid-scale)

At the landscape scale, the dry mixed conifer vegetation community is a mosaic of forest conditions composed of structural stages ranging from young to old trees. Large trees are well distributed in the landscape. Forest appearance is variable but generally uneven-aged and open; occasional patches of even-aged structure are present. The forest arrangement is in small clumps and groups of trees interspersed within variably-sized openings of grass, forb, and shrub vegetation associations similar to historic patterns. Openings typically range from 10 percent of the total stand/state area in more productive sites to 50 percent in the less productive sites. Size, shape, number of trees per group, and number of groups per area are variable across the landscape. Where they naturally occur, groups or patches of aspen and all structural stages of oak are present. Denser tree conditions exist in some locations such as north-facing slopes and canyon bottoms.

At the mid-scale the dry mixed conifer forest vegetation community is characterized by variation in the size and number of tree groups depending on elevation, soil type, aspect, and site productivity. The more biologically productive sites contain more trees per group and more groups per area. Openings typically range from 10 percent in more productive sites to 50 percent in the less productive sites. Tree density within forested areas generally ranges from 30 to 100 square foot basal area per acre (7–23 m^2/ha).

The mosaic of tree groups generally comprises an uneven-aged forest with all age classes and structural stages. Occasionally small patches (generally less than 50 acres (20 ha)) of even-aged forest structure are present. Disturbances sustain the overall age and structural distribution.

Forest conditions in goshawk post-fledging family areas (PFAs) are similar to general forest conditions except these forests contain 10 to 20 percent higher basal area in mid-aged to old tree groups than in goshawk foraging areas and in the general forest. Goshawk nest areas have forest conditions that are multiaged but are dominated by large trees with relatively dense canopies.

Appendix B: Stand Density Dynamics

Density management is the manipulation and control of growing stock (trees) in order to achieve management objectives. The most generally effective indices of growing stock are those that combine some expression of mean diameter and density (Long and Smith 1984). Stand density is a quantitative measure of stocking expressed as trees per acre (TPA) or square feet of basal area per acre (BA). Despite widespread use, density measures like TPA or BA have limited utility, as they have no inherent biological or physiological frame of reference (Smith 1986). Respectively, TPA and BA convey only the average distance between trees of unknown size and species, and the cross-sectional area of the tree at 4.5 ft (1.4 m) above the ground. Reineke's (1933) stand density index (SDI) was considered with our analysis, according to parameters described by Shaw and Long (2010), because SDI accounts for tree size, can be related to a species' maximum physiological density, and is independent of age and of site quality (Daniel, Helms, and Baker 1979).

Percent of maximum stand density is determined based on Reineke's stand-density index (Reineke 1933). Reineke discovered a predictable relationship between quadratic mean diameter-squared (QMD^2) and trees per unit area in dense even-aged stands. Stand density index is a value based on the number of trees per acre at an average stand diameter of 10 inches (25 cm).

The relationship between average size and density of trees in populations experiencing density related or suppression mortality has been shown to be predictable for a number of tree species. This "self-thinning rule" (Yoda et al. 1963) is a fundamental relationship found to be independent of both stand age and site quality. Because of this relationship, a stand density that is desired in the context of a specific set of management objectives can be projected forward or backward to a different stage of stand development.

Those who use SDI—or any index of stand density—as an estimate of growing stock, must assume that the index is proportional to site utilization (Long and Smith 1984). Since the contribution of individual stand components to both total SDI and total site utilization is additive (Stage 1968), SDI can also be used to assess control of growing stock in uneven-aged stands as well as even-aged stands (Long and Smith 1984). Although SDI and the maximum size-density relationship were originally described for pure, even-aged stands, Long and Daniel (1990) have proposed the extension of its utility to uneven-aged and multiaged situations.

Basal area is a widely used measure of stocking; however, SDI is a more descriptive means of expressing stand or group density because SDI is related to average diameter (quadratic mean diameter) and trees per acre. Table 7 is used to demonstrate the usefulness of SDI over basal area, taking two groups or stands of equal basal area, at 60 ft^2 (14 m^2/ha). Basal area alone reveals little difference. However, if stand A has an average tree diameter of 6 inches (15 cm) and stand B has an average diameter of 18 inches (46 cm), it becomes apparent that stand A is considerably more dense, with nine times the number of trees per acre. The more dense condition of stand A provides more canopy cover, hiding cover, and tree-to-tree competition than the condition in stand B. These stand structural differences cannot be detected by basal area stocking alone.

Table 7. Example showing two stands of equal tree basal area but significantly different density

Stand Metric	Stand A	Stand B
Basal area	60 ft^2/ac (14 m2/ha)	60 ft^2/ac
Quadratic mean diameter	6" (15 cm)	18" (46 cm)
Density	306 TPA (756 TPH)	34 TPA (84 TPH)
Stand density index	135	87

The SDI in the Southwestern Region of the USDA Forest Service is calculated based on all live trees larger than 1 inch in diameter (2.5 cm) using one of the following formulas:

(1a) Total stand SDI = total number of trees ≥1" X (quadratic mean diameter/10)1.6

(1b) Total stand SDI = (sum of all tree diameters ≥1"/10)1.6

Note: Formulas 1a and 1b yield similar results in even-aged stand conditions. Formula 1b is used to determine SDI in uneven-aged or multiaged stands.

In even-aged stands of a given quadratic mean diameter (QMD), Reineke (1933) observed that there was an upper limit to the number of trees per acre present in the densest stands. As QMD increases, the upper density limit decreases exponentially. Drew and Flewelling (1979) reached similar conclusions with regard to mean tree volume and density. The exponential slope of the upper limit curve is the same for all tree species. The intercept of that curve, however, is both regional and species specific—higher for tolerant species and lower for intolerant species. The upper limit curve is referenced to the theoretical maximum number of 10-inch diameter trees per acre. The published maximum SDI for ponderosa pine is 450, indicating that the upper limit, or reference, curve passes through 450 TPA when QMD equals 10 inches.

Stand density index is more often expressed as a percent of maximum (see table 5). An SDI of 180, for example, would be 40 percent of the maximum for local ponderosa pine. One would expect the densest possible stands to be clustered between 80 and 100 percent of maximum. Figure 5 illustrates these SDI concepts.

Knowledge of these relationships, along with basic knowledge of plant physiology and resource allocation, permits informed decisionmaking with regard to desired stand structure and development.

Plant foliage produces organic sugars that are allocated for growth and reproduction in this general priority: (1) maintenance respiration; (2) production of fine roots and foliage; (3) flower and seed production; (4) height growth; (5) crown expansion and root extension; and (6) diameter growth and defense mechanisms (Oliver and Larson 1996). To enable biochemical and physiological processes, including the production of carbohydrates, requires sunlight, water, mineral nutrients, suitable temperature, oxygen, and carbon dioxide. These growth factors, in aggregate, form an abstract, non-dimensional "growing space" on any given site. A site's productivity, also known as carrying capacity, will be limited by the scarcest of the six growth factors.

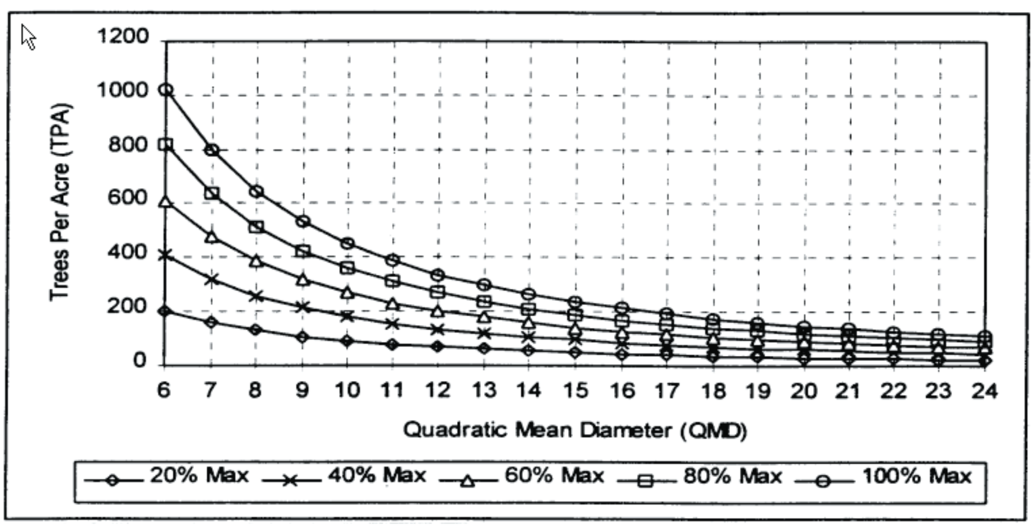

Figure 5. The SDI for ponderosa pine in the southwestern U.S. is described by this family of curves derived from Reineke's equations (Reineke 1933). The top curve is the theoretical "upper density limit." Lower curves indicate percentage of the maximum. Any point on a given curve represents an equal level of physiological density.

Implications of the maximum size-density relationship are as follows:

1. As mean tree size increases, the upper physiological limit of TPA decreases.
2. As a stand's size density trajectory approaches the maximum:
    - Tree competition increases
    - Tree growth slows
    - Trees lose vigor
    - Tree mortality increases

The prospects of individual trees improve as their share of growing space increases, either through superior competitive advantage, or the decline and death of their neighbors. As a tree grows, so does its volume of respiring tissue and the weight of its crown. In order to fuel this new tissue and support more weight, a tree must capture additional growing space. If it fails, the priorities of photosynthate allocation are engaged, reducing tree function in reverse order of priority. When a tree controls insufficient growing space to sustain even maintenance respiration, the tree dies (Oliver and Larson 1996).

Site Occupancy and Growth

Site occupancy refers to the degree to which growing space is utilized by trees. The relationship of site occupancy to stand and individual tree growth is familiar to silviculturists as that depicted by the three zones of Langsaeter's growth curves (Langsaeter 1941). Long and Shaw (2010) have proposed the percent of maximum SDI that correlates with the zone thresholds within growth functions (Long 1985). Figures 6 and 7, and table 3 illustrate the relationship of Langsaeter's growth curves and Long's percent of maximum SDI values to site occupancy, competition among trees, diameter and volume growth in trees, volume growth in stands, species composition, and stem quality.

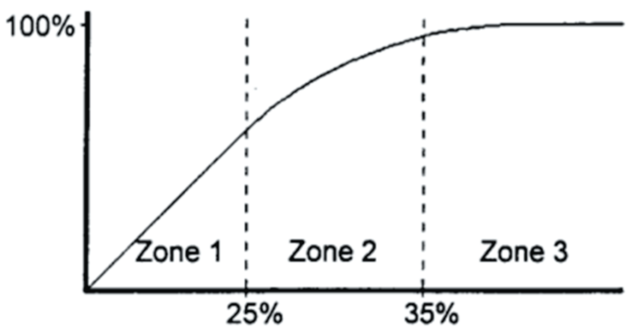

Figure 6. Relationship of annual whole stand growth as a percentage of potential (max SDI), based on Langsaeter (1941), as described in Long (1985).

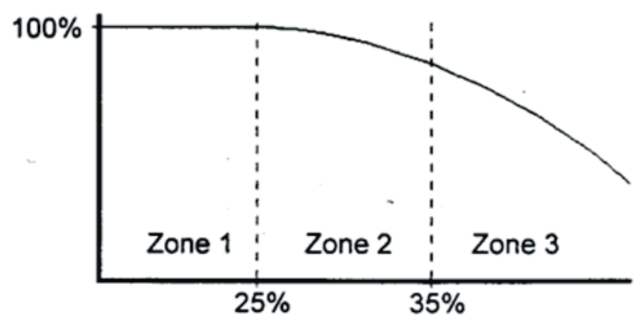

Figure 7. Relationship of annual individual tree growth as a percentage of potential (max SDI), based on Langsaeter (1941), as described in Long (1985).